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# A study of recent changes in Southwest Power Pool and Electric Reliability Council of Texas and its impact on the U.S. wind industry

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ABSTRACT

Due to the increased penetration of renewable energy resources, there has been a lot of activity in the regional transmission organizations such as development of new standards, protocol revisions, new study requirements, changes to modeling procedures etc., in the last five years with a special focus given to wind energy. The key objective of this paper is to identify the impacts and the immediate technological and market related improvements required by the wind industry as a result of such changes in Southwest Power Pool (SPP) and the Electric Reliability Council of Texas (ERCOT). The paper documents the most important activities by following the higher-priority committees, work groups and task forces in both companies along with some of the special projects or initiatives such as sub-synchronous control interaction study, primary frequency response, hub concept and other modeling improvements related to wind energy. The paper provides an analysis of the impact of each change resulting in technology upgrades to wind turbines, modeling improvements by turbine manufacturers and policy/market changes affecting wind farm developers. Finally the paper provides recommendations regarding the requirements and capabilities which the future wind farms and wind turbines need to possess.



**Contents**



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## 1. Introduction

The Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) are the two major organizations which regulate the electricity markets and ensure reliability of the bulk power system in USA. FERC is a federal agency in United States of America formed to provide a strong and reliable national energy infrastructure. FERC's responsibility includes reliable infrastructure, margins and acquisitions, licensing and inspection, compliance and monitoring and has all legal authorities over the interstate sales and rate regulation of electricity [1]. NERC is a non-governmental Electric Reliability Organization (ERO) formed to ensure reliable operation by developing and enforcing appropriate reliability standards, monitoring the power system and familiarizing the industry personnel with proper training and seminar. NERC is certified by the Federal Regulatory Commission to enforce the standards, not only for the generation owners but also for all the users, property owners and operators. NERC is not directly regulated by FERC rather it is a self regulatory organization. FERC oversees the NERC operation and provides important suggestions when necessary [2]. A map indicating the NERC regions is shown in Fig. 1.

The Electric Reliability Council of Texas (ERCOT) and the Southwest Power Pool (SPP) fall under the regional entities formed by NERC and the Regional Transmission Operators (RTOs) formed by the FERC. This region of the country has been the hotbed of wind energy development for the past several years, with at least 28% of all new U.S. wind energy project construction occurring in these 8 states, each of the last four years.

Due to the increased penetration of renewable energy resources, there has been a lot of activity in the regional transmission organizations such as development of new standards, protocol revisions, new study requirements, changes to modeling procedures etc., in the last five years with a special focus given to wind energy. The key objective of this paper is to identify the impacts and the immediate technological and market related improvements required by the wind industry as a result of such changes in SPP and ERCOT. The paper documents the most important activities by following the higher-priority committees, work groups and task forces in both companies along with some of the special projects or initiatives such as sub-synchronous control interaction study, primary frequency response, hub concept and other modeling improvements related to wind energy. The paper provides an analysis of the impact of each change resulting in

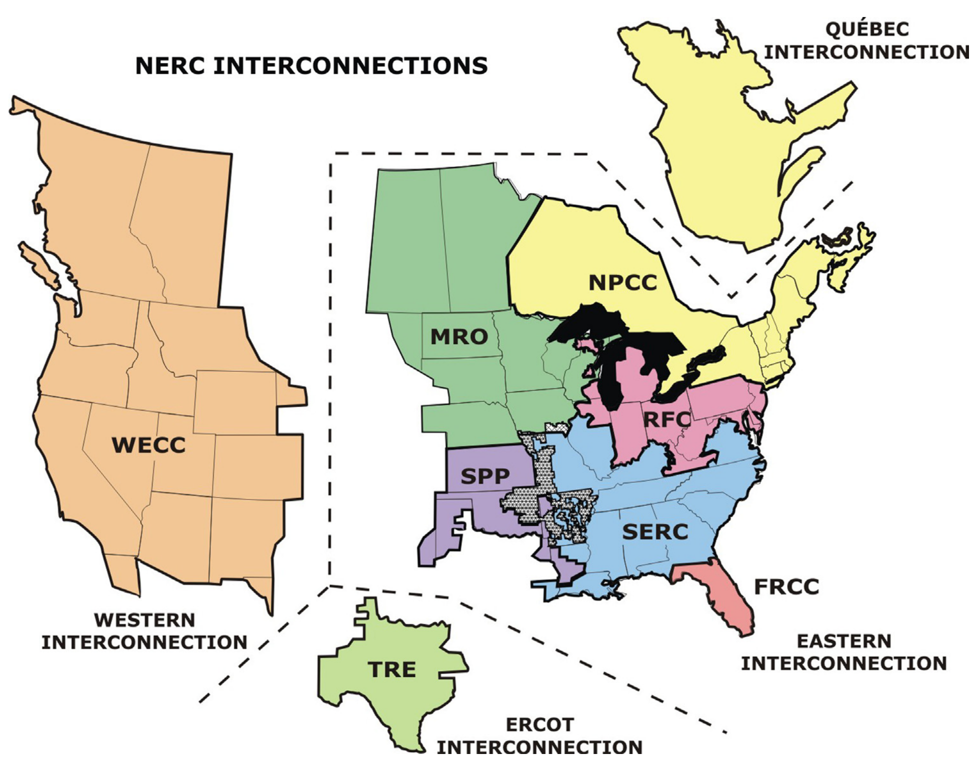


**Fig. 1.** NERC regions in USA [27].

technology upgrades (hardware/control /protection) to wind turbines, modeling improvements by turbine manufacturers and policy/market changes affecting wind farm developers.

This paper starts with an overview and wind energy status in SPP and ERCOT in Section 2 which includes information such as responsibilities, footprint, wind generation capacity etc. The most important activities in SPP and ERCOT affecting the wind industry in recent times and in the near future are discussed in Sections 3 and 4 respectively. The limitations of the current wind turbines and wind farms are discussed in Section 5. Section 6 provides research directions, recommendations and capabilities that the future wind turbines and wind farm owners need to possess to comply with the recent/proposed changes in SPP and ERCOT.

## 2. An overview of SPP and ERCOT

### 2.1. SPP

The Southwest Power Pool (SPP) is one of the nine Independent System Operators (ISOs)/Regional Transmission Operators (RTOs) in North America. RTOs are the "air traffic controllers" of the electric power grid. They do not own the power grid, but independently operate the grid minute-by-minute to ensure that power gets to customers and to eliminate power shortages. SPP provides services to members in nine states: Arkansas, Kansas, Louisiana, Mississippi, Missouri, Nebraska, New Mexico, Oklahoma, and Texas. The SPP transmission system includes almost 48,368 miles of high-voltage lines including voltage levels of 69 kV, 115 kV, 138 kV, 161 kV, 230 kV, 345 kV and 500 kV. The primary services provided by SPP to its members and customers are reliability co-ordination, Tariff administration, Regional Scheduling, Transmission expansion, Market operation, compliance and training [3]. The SPP region covers 370,000 square miles, and has a capacity of about 63 GW. SPP members serve over 6.2 million households. Of the renewable resources available, wind is in the most advanced stage of development in the SPP region [3].

#### 2.1.1. Wind energy status in SPP

Southwest Power Pool (SPP) has enormous wind energy resources and had tremendous growth in the integration of wind power in the past five years. Most of the wind resource concentration lies in Nebraska, Kansas, western Oklahoma and portions of New Mexico and Texas. SPP has 8.607 GW of wind generation capacity from 106 sources as of February 2014 [5]. Wind generation supplies an annual average of 7.6% of the total system generation but has reached a maximum of 14% in few months of the year [6]. The wind capacity and wind generation in SPP since February 2012 is shown in Fig. 2. SPP is facing severe congestion to dispatch power from the areas of high wind energy potential.

### 2.2. ERCOT

ERCOT is the primary Independent System Operator (ISO) in Texas. On December 1, 2010, ERCOT shifted from a zonal market to nodal market. With this move, ERCOT ensured improved use of generation resources through unit-specific dispatch, more efficient congestion management, accurate price signals, and improved ability to efficiently integrate the renewable energy sources. The nodal market will consist of Day Ahead Market (DAM) to co-optimize energy, Ancillary Service (AS) capacity and congestion revenue rights. The primary objective of DAM is to arrange energy and ancillary services along with price certainty for the next day. ERCOT ensures power supply to almost 24 million consumers, which is nearly 85% of the electric load, and covers 75% of the land

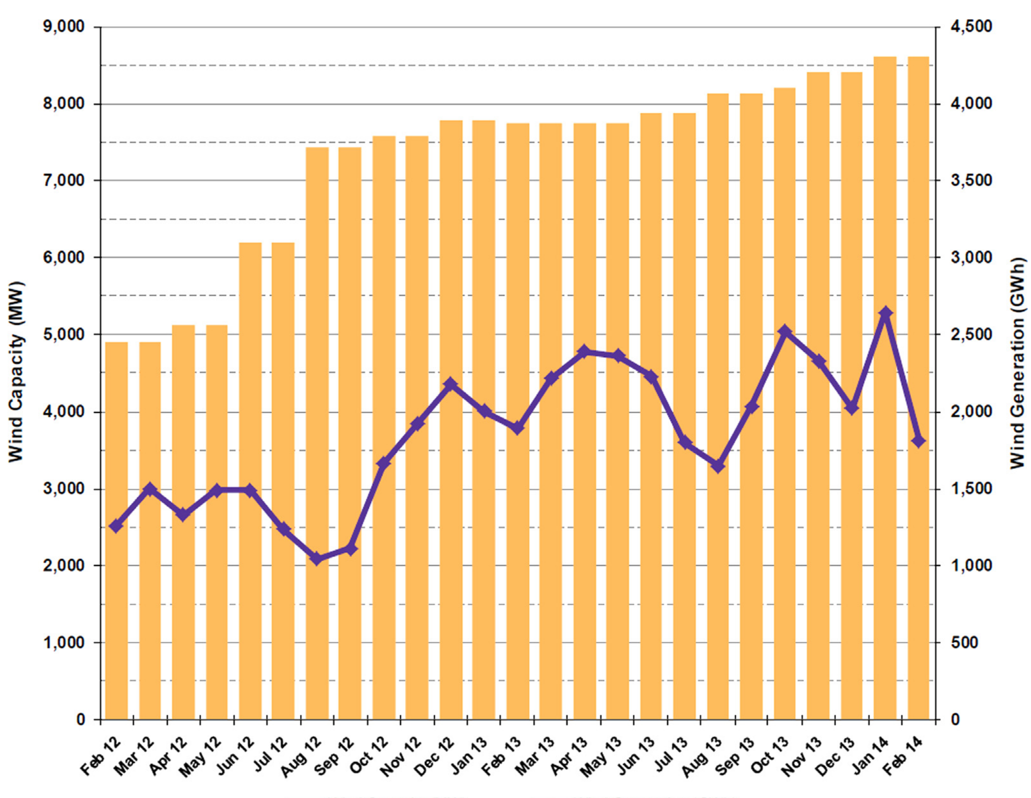


**Fig. 2.** Amount of wind generation and the total wind capacity in each month of the year in SPP from February 2012 to February 2014 [6].

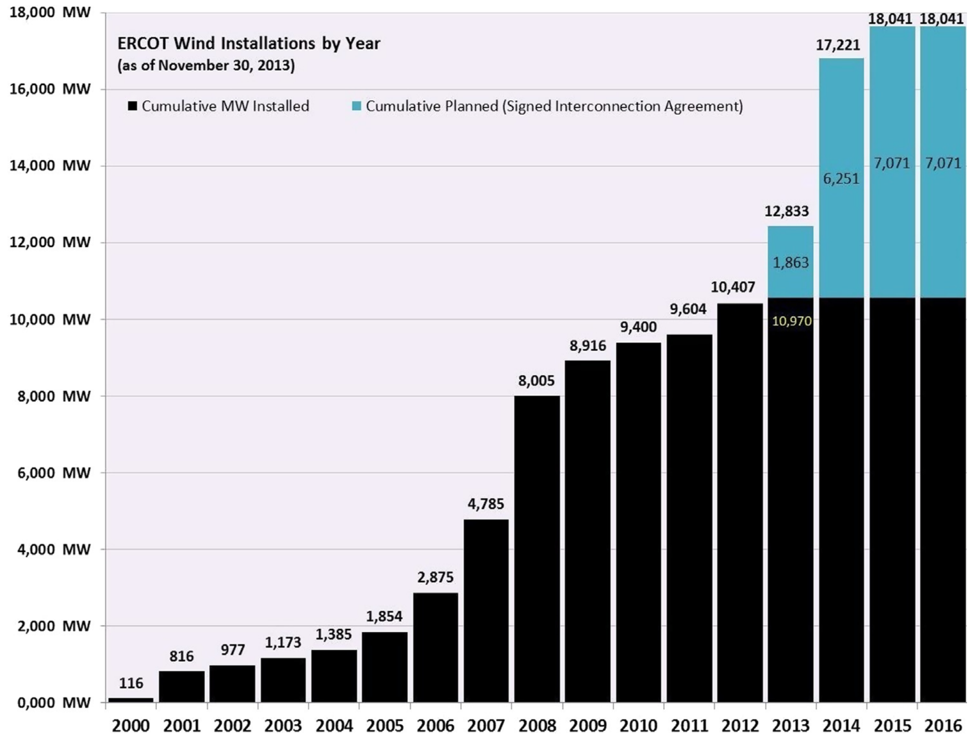


**Fig. 3.** Amount of wind power installations per year in ERCOT from year 2000 and projected until 2016 [16].

area in Texas. ERCOT's current installed capacity is 74 GW, 56% of the total generation is generated from natural gas while wind energy supplies 14% of the total installed capacity [4].

#### 2.2.1. *Wind energy status in ERCOT*

Due to the geographical attributes, ERCOT has a huge potential for wind. Currently, the ERCOT region is leading the nation by the amount of wind energy it produces, and holds the fifth place in the world. ERCOT has a total generation capacity of 74 GW out of which wind farms contribute 11.255 GW as of November 2013. The annual average of wind energy generation was 9.9% of the total energy consumed during 2013. ERCOT has experienced large amounts of wind penetration several times a year with the latest being 28% of the total energy consumption or 9.674 GW supplied by wind farms [15]. ERCOT has undertaken several transmission projects worth $9.3 billion to enhance the grid integration of wind energy. The Competitive Renewable Energy Zone (CREZ) was formed to facilitate the growing wind energy. ERCOT started with an initial capacity of 116 MW during the year 2000, but now plans to install 17.221 GW of wind energy by the end of 2014. ERCOT is currently tracking 22.6 GW of wind energy interconnection requests [16]. The amount of wind energy installed each year in ERCOT since 2000 and proposed wind farms till 2016 is shown in Fig. 3.

## 3. Policy changes and technological issues in SPP affecting wind industry

In the last couple of years, several policy changes affecting the markets and technology have been made in SPP to accommodate more wind energy without comprising the reliability and economics. The changes, which have a major impact on the wind industry, are discussed in this section.

### 3.1. *Standards under development*

#### 3.1.1. *Under frequency load shedding*

In order to ensure reliability of the bulk power system, NERC required SPP to develop regional Under Frequency Load Shedding standards (UFLS) which will help to restore the system following a frequency event due to sudden loss of generation or load. The standard includes all generator owners, including wind, to comply with minimum frequency protection requirements. All generator owners should ensure that their units will not trip at any frequency above generator under frequency curve, and below generator over frequency curve [7,14] as shown in Figs. 4 and 5.

#### 3.1.2. *Generator loadability standard*

Analysis of several events in the power system has shown unnecessary tripping of generators during system disturbances which did not have any direct impact on generators [8]. Such tripping would increase the severity and duration of the disturbance. The criterion for load responsive protective relays is established by the generator loadability standard, in order to obtain dynamic support from the generators during transient system events. This reduces the severity of the disturbance and prevents the system from being vulnerable to further disturbances. The standard provides relay requirements for generator units, generator station transformers and auxiliary transformers. The relay settings which are applicable to wind farms and wind turbines are given in the reference [8].

### 3.2. *Transition to integrated marketplace in 2014*

SPP has moved from the Energy Imbalance Service (EIS) to the integrated marketplace on March 1, 2014. In the Energy imbalance market, participants buy and sell electricity in wholesale. The excess energy required by the utility company should be bought at real time prices in the market to meet the demand. In

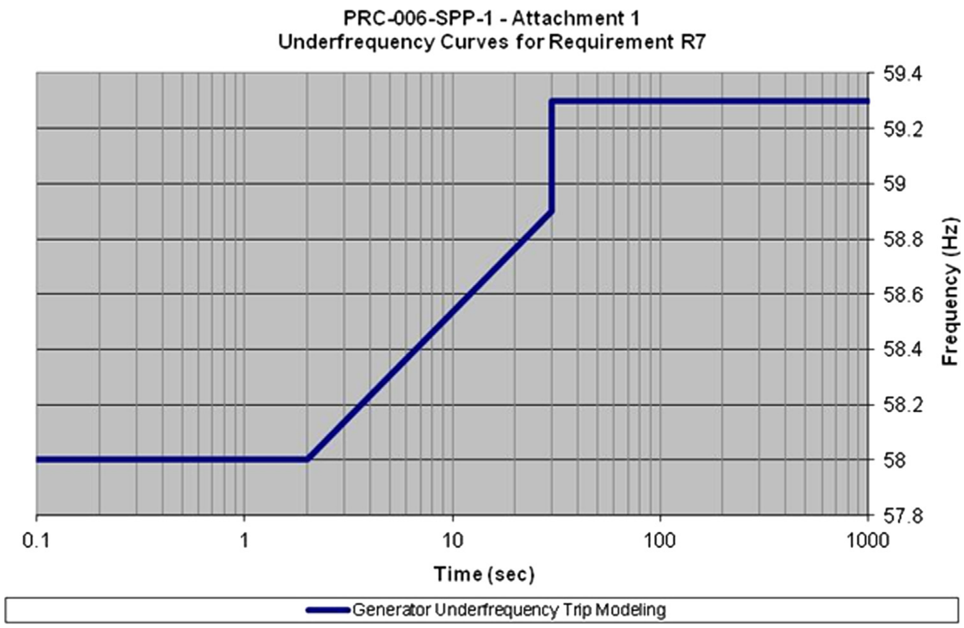


**Fig. 4.** Generation under frequency trip modeling [7].

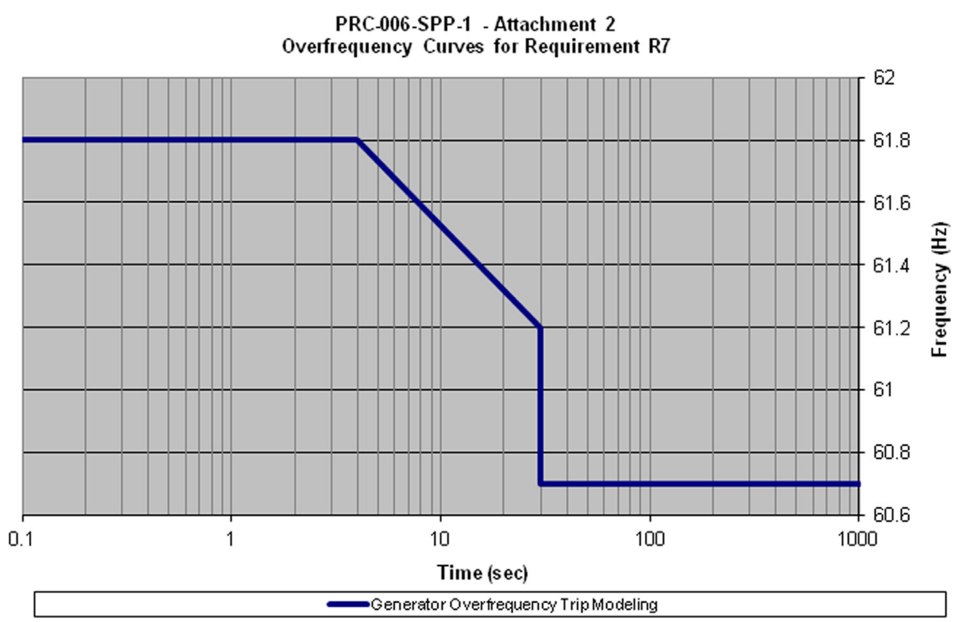


**Fig. 5.** Generator Over frequency trip modeling [7].

the EIS market, each market participant makes arrangements for the next day, in order to meet its own demand along with the operating reserves. This limits the choice for the market participants and leads to increased costs by running a high cost generation, even if a less expensive one is available in other regions of the market [9].

The integrated marketplace includes day ahead market with transmission congestion rights. In the new market, the integrated market place will select the generators supplying power on the next day based on maximum cost effectiveness.

This will allow all market participants to have greater access to generation over a wider region, which replaces the current procedure of each utility company committing to their own generation. In addition, greater access to reserve energy is provided to all members thereby facilitating greater integration of renewable energy in the footprint. In the energy imbalance market, several balancing areas in the SPP region ensure the reliability, electricity supply, and plans for the future in their respective region. But in the integrated market place, SPP acts as a consolidated balancing authority (CBA) combining all the existing balancing authorities into one [9]. The regulation reserves that has to be maintained by each balancing area reduces, as the CBA will maintain the frequency balance, stability, ensures reliability and meets the NERC reserve requirements across the entire SPP footprint. The CBA will facilitate centralized unit commitment, in which the Day Ahead market determines what generation should be utilized for maximum regional benefit [9].

### 3.3. Wind to be declared as dispatchable energy resource

Currently, in the energy imbalance service market, all wind farms are considered as non-dispatchable in spite of few wind farms being capable to dispatch down when required. In the Integrated market place from 2014, wind farms are required to register as dispatchable variable energy resources (DVER). DVERs are those which can be dispatched down by the transmission owner during emergency conditions [10]. Those resources which cannot be dispatched down or incrementally reduced but can be completely taken offline are registered as non-dispatchable variable energy resources (NDVER). Conditions such as re-dispatching the congested lines and excess generation conditions can be effectively managed by registering resources which are capable to dispatch down as DVERs. DVERs are required to supply resource offer curves and are treated similar to other dispatchable resources in terms of dispatching down by SCED algorithm based on the price offered by the resource; while NDVERs are dispatched down manually if required, to ensure the reliability of the system.

The following rules apply if a wind farm is registered as a DVER [10]:

- The minimum emergency and economic operating capacity limit should be set to zero.
- DVERs are required to provide a name plate capacity rating during market registration. The maximum ramp rate in the ramp up and ramp down curves provided in the resource offer should not exceed 10% of the name plate capacity divided by 5 min.
- The least of resource offer or SPP output forecast is set as maximum operating limit.
- The greater of SPP output forecast or actual output from the wind farm is set as maximum operating limit in real time balancing markets.
- The wind farm is allowed to submit a 10 min ahead forecast in real time balancing market via ICCP.

### 3.4. Improvements in modeling procedures

In SPP and other regional entities, three modeling related tasks are performed for the following reasons: (1) generation interconnection studies, (2) transmission planning, and (3) operations. Generation interconnection studies are performed when a new generation plant is requested and requires a pretty accurate model representing the generator characteristics in the bulk power system. Planning studies are performed to plan transmission for several years in the future, and operation studies are the day to day studies performed to ensure reliability. Currently, the wind farm models are not accurately represented in planning and operations studies. Wind farm models are approximated as a synchronous generator with same name plate capacity which led to inaccurate results and wrong conclusions. The Model Improvement Task Force (MITF) in SPP released a white paper addressing various modeling issues, and provided recommendations to improve the modeling process. Some of the key issues which are related to wind modeling are given below [11]:

- Uniform standards to model wind generation are not available.
- Netting of distributive generation along with customer load leads to inaccurate results.
- Currently, wind generators with long term firm, non-firm, or customer owned are not identified under proper types with respective IDs as done with loads. Due to such lack of IDs, some of the generators are considered as non-firm and are not dispatched leading to loss of revenue for few generation owners.
- Lack of frequent updates to the base case model used by the planning and operations studies with the new generation interconnections.
- Inaccurate representation of reactive power capabilities in base case models, even if wind turbines are modeled.
- Lack of good generic models for wind turbines in PSS/E version 30.
- The models provided by the wind turbine manufacturers are not allowed to be added to the base case models for confidentiality purposes. This leads to a significant difference between generation interconnection and planning and operations studies.
- Transmission owners and utility companies face the problem to access few models due to sensitive and proprietary data which makes it difficult to develop solutions to certain study related requests.

Following are the recommendations proposed by MITF for the issues above [11]:

- Development of uniform generator identification along with generator IDs to differentiate long term firm, non-firm, and behind the meter projects.
- The base case model should be updated immediately after the execution of the generation interconnection agreement.
- The data submitted to the base case model should be verified with the generation interconnection data to ensure an accurate model is included for the respective plant.
- Generator owners should be asked for a non-proprietary model such that it can be used in the planning and operations studies.
- Requesting additional data with more details from the members and customers.
- A non-disclosure agreement should allow SPP to share the required data with transmission owners.

### 3.5. Hub concept

Due to the increase in the number of wind generation interconnection requests, there are several cases where wind developers have requested interconnections geographically close to each other, especially in areas of high wind potential [12]. Each wind farm develops its own substation where it taps the transmission line and interconnects into the grid. As a result, the transmission line consists of several taps within close proximity which leads to operating and reliability issues such as the following [12,13]:

- Opening one breaker due to a contingency in one of the substations will cause current surges which will cause other breakers to operate.
- Due to the increased number of taps, the possibility of overvoltage, both in steady state and transients is high. This has to be prevented by installing reactors at each tap on the transmission line.
- Studies performed for the mitigation of surges and overvoltages is highly expensive, time consuming and very technical.
- Placing series reactors in a transmission line will reduce the power handling capacity of the line.
- The series reactor has to be disconnected during heavy loading conditions. If, due to some reason, the reactor does not get disconnected, voltage depression leading to a complete voltage collapse might occur.

Considering all the issues above, Area Generation and Connection Task Force (AGCTF) in SPP has decided to minimize the number of taps on the transmission line by proposing generation hubs [12]. A generation hub is a substation which collects generations from multiple wind farms (which are located geographically close) at one common point and interconnects to the transmission system. Hubs are designated only in areas of high wind potential and where large numbers of interconnection requests are filed. The interconnection customers will be required to direct their generation to the hub rather than building a separate project substation for each project. Hubs will be established only on 345 kV or greater lines which has at least three generation interconnection customers proposing to interconnect within 10 miles. Either switching transient occurrences or increase in cost to add a substation will trigger SPP to designate a hub in a specific location. Hubs will not be designated within a distance of 23 miles from another hub. Either existing/planned substation or future substations identified in Integrated Transmission Planning studies performed by SPP will be designated as hubs [12]. One big issue with the hub concept is blocking of generation developers by previous customers to access the hub. As a solution to this problem, SPP came up with the concept of spokes which terminates at the hub built by SPP. Spokes are radial lines (gray area shown in Fig. 6) requested by generation developers and built for a voltage above 345 kV to carry power in the range of 800–1000 MW. Spokes are not overbuilt for future interconnection purposes to ensure minimum cost allocation for generation interconnection customers. The hub concept is illustrated further using a scenario as shown in Fig. 6. Three wind farms named as wind farm A, wind farm B and wind farm C are 15 miles geographically apart from each other and have a point of interconnection at points A, B & C respectively as shown in Fig. 6. Under normal cases, the three wind farms would have tapped the 345 kV transmission line at three different points leading to the drawbacks discussed above. But using the hub concept, all the three wind farms are interconnected at a common interconnection substation or spoke as represented by S1 in Fig. 6. This reduces the number of series reactors to one at substation S1. A common transmission line would be built from spoke S1 to hub H1 where it is interconnected to the transmission system thereby transferring power at reduced costs.

SPP believes that the hub concept would reduce the costs for generation interconnection customers, minimize environmental issues, and increase reliability. Generation customers may request an exemption if the wind farm lies in the gray area, unable to access the hub or the process gets delayed a lot due to other studies, or if the customer incurs excessively high costs [12].

## 4. Policy changes and technological issues in ERCOT affecting wind energy

ERCOT is facing several technology and market issues in an effort to accommodate high wind generation leading to several changes discussed in this section.

### 4.1. Subsynchronous control interaction

In 1970, the first occurrence of sub-synchronous resonance (SSR) took place as a result of energy exchange between the series compensated line and the synchronous generator. The resonance frequency of the transmission line matched with the resonance

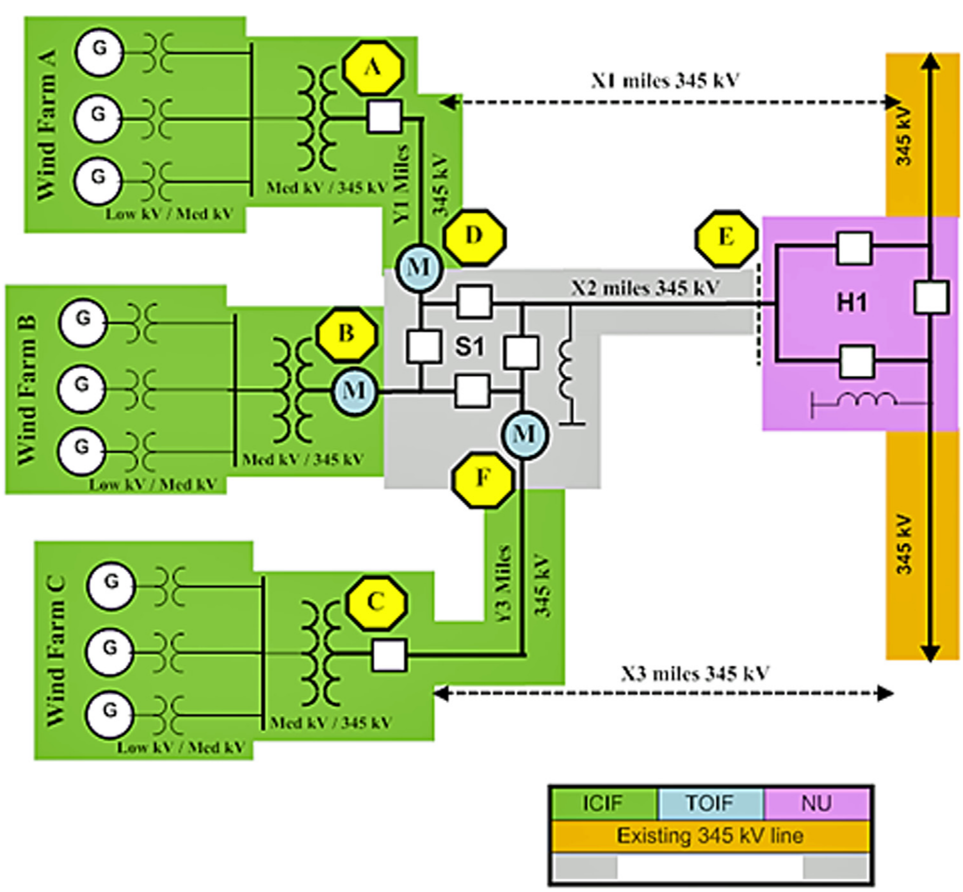


Fig. 6. Hub and spoke configuration proposed by SPP [12].

frequency of the generator which lead to devastating results by damaging the generator shaft. SSR has been studied in great detail and solutions to mitigate the issue were proposed in the literature. Recently, an interaction between series compensated lines and the power electronic devices in a wind turbine (HVDC link, SVC, wind turbine) occurred, which is named Sub Synchronous Control Interaction (SSCI). SSCI is a highly technical issue that has been found due to grid integration of wind turbines, and has gained high importance in ERCOT.

The first SSCI incident occurred in the ERCOT region in 2009. The single line diagram of the affected area is shown in Fig. 7 below. Two wind farms named as wind system A and wind system B are connected to Zorillo substation as shown in Fig. 7. The zorillo substation is connected to ion hill substation and a series compensated transmission line to Rio Hondo in a T fashion.

Following a static wire initiated fault at LON HILL substation, two wind farms of 485 MW capacity were left in radial connection with a 50% compensated transmission line. Within 200 ms, sub synchronous oscillations grew and the voltage reached 195% of the nominal value causing damage to the crowbar circuit in the wind turbine and tripping of additional transmission facilities. Finally, the Sub synchronous oscillation was cleared by bypassing the series capacitors after 1.5 s [17]. The voltage and current variations during the sub synchronous oscillations are shown in Fig. 8.

Following the incident, ERCOT requested ABB to carry out “ERCOT CREZ Reactive Power Compensation Study” to identify the risks associated with SSCI in detail. The study showed that type 3 wind turbines with doubly fed induction generators were more vulnerable to SSCI and proposed a solution at a transmission level, and provided recommendations to modify the wind turbine controls [18].

As a result, ERCOT came up with new study requirements for the wind farm owners and turbine manufacturers to be included in the generation interconnection process. ERCOT staff will perform an initial steady state security screening study for each generation interconnection request. The objective of this study is to find out if any resonant frequencies exist, looking into the grid from the wind farm point of interconnection, when scanned using the frequency scanning tool in PSCAD. If the study shows existence of such resonance frequency, ERCOT requires the wind developers to perform detailed electromagnetic simulation studies and implement solutions to mitigate SSCI before the commercial date of operation [19].

### 4.2. Primary frequency response

Stable operation of the grid depends on the balance of load and generation. The response of generator and the load is extremely important in the event of frequency deviation in order to bring back the frequency to its nominal value, which is regarded as the frequency response. Depending on the response time, frequency response has been divided into three classifications [20].

- Inertial Response is used to slow down the initial rate of decline in the frequency. Inertial response acts within the first few seconds of the frequency deviation.
- Primary Frequency Control is used to bring back the frequency to a steady state level. Primary Frequency Control lasts in the range of 1–10 s.
- Automatic Generation Control (AGC) is used to bring back the frequency to its nominal value. AGC operation may vary within a time range from 10 s to 10 min.

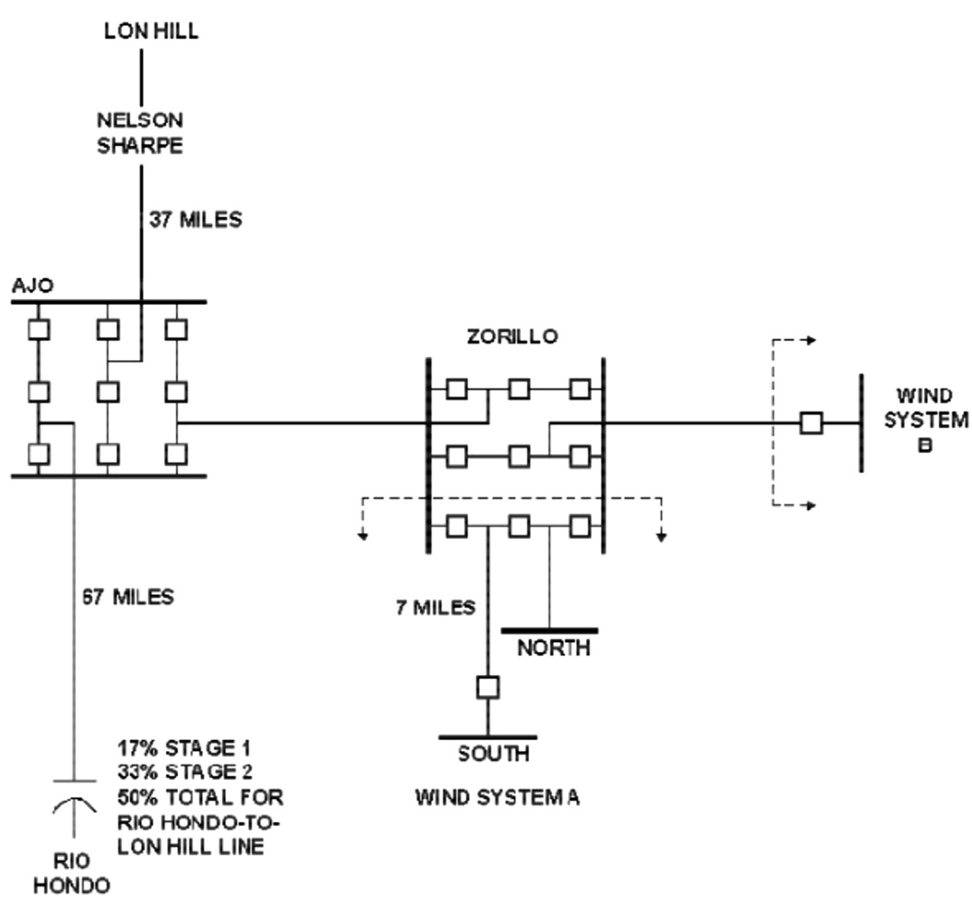


**Fig. 7.** Single line bus diagram of the SSCI incident network [17].

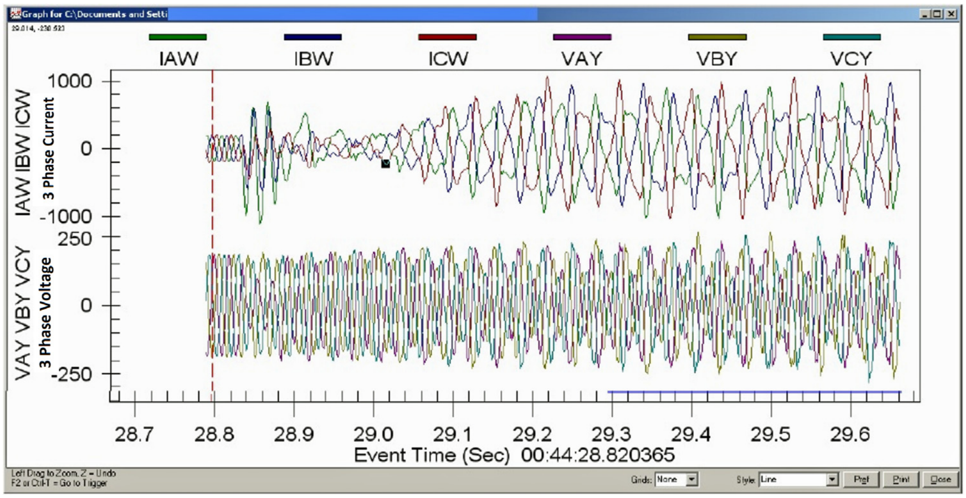


**Fig. 8.** Current and voltage value during fault and sub synchronous oscillation [17].

Wind turbines are connected to the grid through the power electronic converters and do not provide frequency response naturally. ERCOT requested Ernest Orlando Lawrence Berkeley National Laboratory to conduct a study evaluating the frequency response of the bulk power system. A dynamic simulation case was built with 735 generators and 116 GW of total generation capacity using Siemens PTI/PSSE software. Results of the study showed a frequency decline in the ERCOT region in certain conditions evaluated [21]. To arrest the frequency decline, ERCOT defined new frequency response requirements which included the wind power generating units.

As per the newly defined standards, wind farms are required to provide primary frequency response proportional to the frequency deviation; 70% of the required response should be provided within 14 seconds from the frequency event. All automatic control systems in wind generating resources (WGR) are required to have an adjustable dead band. ERCOT has decreased the dead band from 36 mHz to 16 mHz. The droop characteristics of WGR should be 5%, which means 5% change in the frequency requires 100% change in the output of the WGR. This requirement is similar to the conventional generating units. Synthetic inertia may provide quick response to arrest frequency decline during extreme low loads. ERCOT added a frequency threshold value to deploy the synchronous condensers [22].

### *4.3. Power factor*

Generating units greater than 20 MVA connected in a point of interconnection needs to provide voltage support in the ERCOT region. Recently, ERCOT clarified the power factor and hence the reactive power required for providing the voltage support service (VSS) from wind powered generating resources. Previously, ERCOT required the generating units to provide 0.95 lagging power factor at all voltage levels, but in reality it is not always possible to provide 0.95 lagging power factor. According to the new requirements, an over excited source should supply power to the transmission system at a power factor of 0.95 lagging or less determined by the generating units maximum net power to be supplied. Similarly, an under excited source should supply power at 0.95 leading power factor or less [23].

WGRs installed after February 2004, need to provide reactive power support to maintain the voltage profile developed by ERCOT, and the related Transmission Service Provider. If the existing WGRs design does not allow them to meet the Reactive Power requirements, then it must conduct engineering studies or conduct performance testing to determine their actual Reactive Power capability, and the results should be accepted by ERCOT. Reactive power requirements applicable to these WGRs will be greater of the leading or lagging reactive power capability found using the engineering study. Existing WGRs, whose current design allows them to meet the established new requirement, should provide the required reactive power and might need to provide ERCOT with the actual capability by conducting engineering studies [23].

### *4.4. ERCOT modeling updates*

Several changes with respect to modeling have been taking place in ERCOT. It has updated the modeling software from Siemens PTI/PSSE version 31.0 to version 32.0. All the network models and generator models used for system planning and stability study have been remodeled using the new version. Any new wind generation unit now needs to submit their detailed model to ERCOT using the PSSE version 32.0 [24]. As per the new short circuit study procedures, the transmission service providers are allowed to ask for detailed wind turbine models, whereas previously the detailed models were not shared by ERCOT. In such a case, a black box model with all the inputs and outputs defined can be an option for the wind turbine manufacturers to secure the confidentiality of their detailed model [25].

### *4.5. Wind forecasting methodology*

During 2011, ERCOT updated the wind forecasting methodology to provide a more realistic wind output prediction. The previous wind forecast method known as the 80% rule use to provide an unnecessarily conservative wind output prediction. As a result, wind farm owners needed to commit for Reliability Units (RU) to maintain the grid stability. Reliability Unit Commitments (RUC) is expensive and adds excessive amount of charges in the operational cost of the wind farm. The new procedure known as the 50% method will provide a more realistic output and reduce the operating cost for the wind farm owners. In addition, the updated method will help better planning by accurately predicting wind energy output from the Wind powered Generation Resources [26].

## 5. Limitations of currently available wind turbines and wind farms

The key limitations in the current wind turbine modeling, wind farm design and the modeling practices used are summarized in this section as given below.

- Due to increasing wind energy penetration, there has been a huge effort by the transmission operators to formulate standards, which treats wind power integration close to conventional power plant, in a grid reliability and economics perspective. The current wind farms do not comply with all the standards such as protection, frequency response etc which the conventional power plants have implemented.
- The reactive power study conducted by the model development working group showed the lack of reactive power support for transmission lines above 60 kV to maintain the voltage within $\pm 5\%$ of the nominal rating. The issue is more dominant in the newly planned 345 kV lines in SPP. The voltage stability issue gets further worsened due to the intermittency of wind power plants and limited reactive power support range from the wind turbines, leading to the requirements for more reactive power compensation devices.
- The nature of sub-synchronous oscillations between a conventional power plant and the grid are well studied and mitigation techniques are already implemented. But, the grid is being exposed to a new reliability threat due to resonance interactions with wind power plants such as SSCI. No mitigation techniques to prevent SSCI are available in the literature yet.
- The power electronics in the wind turbine isolates the turbine generator from the grid. This prevents the wind farm from providing inertial and primary frequency response to the grid. As a result, the wind farms worsens the grid situation leading to a blackout in the event of a frequency dip. Techniques to provide frequency support by the wind farms have not yet been implemented in all wind turbines.
- The current wind farm and wind turbine SCADA capabilities might not be fast enough to follow the dispatch commands of the transmission operator during an unexpected fault such as frequency event or SSCI.
- The lack of accuracy of the currently available wind forecasting tools is one of the major problems faced both the grid operators and wind farm owners. Wind forecasting is used to predict the energy production for the next day and would be used to bid electricity in the day ahead markets (DAM) and real time markets. Deviating from the energy bid will lead to revenue loss for wind farm owners and reliability threat for grid operators.
- Lack of accurate modeling of wind turbines lead to inaccurate results in bulk power system studies.
- The models provided by the wind turbine manufacturers are significantly deviant from the real wind turbine output in few cases. Hence, the wind turbine models are over simplified and are not validated with the real wind turbine hardware output.
- Non-proprietary wind farm or wind turbine models are not developed. This leads to inaccurate results in planning and operations studies conducted by the grid operators.

## 6. Research directions for future wind farms & wind turbines

The impacts of changes in SPP and ERCOT discussed above are analyzed in detailed. Further research directions as a result of all these changes are identified and classified into three types as mentioned namely, a. research directions for wind turbine manufacturers from a technology perspective, b. research directions for wind farm developers to comply with the procedural changes, market changes and technological changes and c. research directions to meet the current and future modeling requirements for turbine manufacturers and software consultants. The requirements and capabilities which the future wind turbines and wind developers need to possess in order to accommodate the above changes and overcome the limitations are briefly discussed in the following sections.

### 6.1. Research direction for wind turbine manufacturers

All wind turbines which are planned in SPP or ERCOT footprint should possess the following capabilities:

- Although most of the wind turbine converters are capable of handling a wider frequency range of $\pm 3$ Hz deviation from the nominal frequency, it should be ensured that the power ramp up and ramp down rates in MW are in compliance with the under frequency load shedding standard in SPP [28].
- All wind turbine generators, padmount, auxiliary and generator station transformers should be capable of load responsive protection relays. The relay settings should be based on the respective grid characteristics to which the wind farm is connected, such as MW and MVAR ratings of wind farm, grid voltage, nominal currents etc. It should be ensured that the protection scheme is in compliance with the generator loadability standard in SPP.
- Improving the reactive power range of the wind turbines is highly essential and required to maintain the stability of the system. In ERCOT, the wind turbines should be capable of providing power at 0.95 lagging or less power factor during overexcited conditions, and 0.95 leading or less during under excited conditions to maintain the voltage profile at interconnection point.
- New Wind powered generating units in ERCOT should provide proper proof that the proposed wind turbine model is free from SSCI issues in the series compensated transmission line. The existing and new wind farm owners with the help of the wind turbine vendor should build dynamic models in PSCAD, Matlab or equivalent engineering simulation tool, using the actual ERCOT network model to carry out the SSCI studies. The model and the results of the studies should be available at all times and should be supplied upon receiving a request from ERCOT.
- Wind powered generation resources in ERCOT should be capable of providing the frequency response stated by ERCOT. The wind turbine control system should be updated to comply with the required droop characteristics and allowable dead band. Compliance with the requirements should be examined using dynamic simulation [28].

### 6.2. Research directions for wind farm developers

Declaration of wind farms as DVERs in SPP's integrated market place will require an improvement in SCADA capabilities of both wind farms and wind turbines. The wind farm SCADA should be able to respond to the communication signals from the SCED algorithm to dispatch down the output when required within a short period of time in the range of 5 min. The wind turbine SCADA will receive signals from the wind farm supervisory control to change the control set points as per the SCED requirements. The complexity and the cost involved for both wind farm and wind turbine SCADA will increase to perform the required tasks.

- In addition to the SCADA complexity, resource offers for the day ahead market and 10 min ahead forecast for the real time

**Table 1**
Modeling software used for bulk power system studies in regional entities.

| Regional entity | Modeling software used |
|---|---|
| ERCOT or TRE PSS/E version 32 | PSS/E version 32 |
| SPP | PSS/E version 32 |
| FRCC | PSS/E |
| SERC | PSLF & PSS/E |
| MRO | PSS/E |
| RFC | PSS/E or PSLF |
| WECC | PSLF |
| NPCC | Both PSS/E and PSLF are being used by members |

balancing market in the integrated market place, demands an improvement in the accuracy of wind forecasting methodology at wind farm level and the wind turbine anemometer. Better forecasting reduces the economic uncertainty and ensures reliable operation of the power system.

- Implementation of the hub concept in SPP might include long radial lines between the wind farm substation and the point of interconnection on the transmission line. This results in an increased investment in the reactive power sources, both reactive and capacitive for the wind farm developers to regulate the voltage in light and heavily loaded conditions. Selection of wind turbines with wider reactive power capabilities will always be an option to reduce some of these costs. In addition, concentrated reactive power sources such as cap banks will result in transient voltage spikes during turn on and turn off, and reactors will reduce the power that can be carried in a transmission line. Hence, distributed reactive power supply from all wind turbines will be a better choice for the wind farm and the transmission system.
- To comply with the changing interconnection process in ERCOT, wind farm developers are required to register as an Interconnection Entity first. Wind farm developers along with the wind turbine vendors need to ensure that the proposed wind turbine model will satisfy the mandatory ERCOT standards, even before applying for registration. Failure to provide proper proof of compliance with standards will result in automatic rejection of the registration application without performing any further study by ERCOT.

### *6.3. Research directions to meet current and future modeling requirements*

All regional entities across the US have been putting a lot of effort into improving the modeling procedures to reduce the gap between the software outputs and the real plant output. The modeling requirements related to wind which are currently in place, and planned to be implemented in the near future are discussed in the following points:

- PSS/E and PSLF are the two software packages widely used in the US to conduct various studies in the bulk power system. The software used by each regional entity is provided in Table 1.
- A PSS/E and PSLF model should be available for each wind turbine. Most of the regional entities especially SPP and ERCOT require the PSS/E model in version 32, although in few cases, a model in version 30 should be provided.
- The generation working group in SPP developed a wind capability spreadsheet as per the requirement of the NERC model validation task force [13]. The spread sheet is planned to be passed on to all wind farms to record the plant active and reactive power output on an hourly basis, in order to forecast the generation capability in each month of the year. Another purpose of this spreadsheet is to validate the software output produced by the model with the real plant output. Wind farm owners will be requested to provide a more accurate model which is close to the real characteristics of the turbines used. Hence, all wind turbine manufacturers should ensure that the models provided contains an accurate representation of all the details required for a bulk power system simulation.
- The wind farms are represented as synchronous generators with equivalent name plate capacity in base case models used for planning and operations purposes. This is due to lack of access to proprietary wind turbine models provided only for generation interconnection studies. Hence, most regional entities are planning to have a proprietary/more detailed model for generation interconnection studies and a non-proprietary/public model for transmission related studies. Therefore, all wind manufacturers will have to provide a non-proprietary model in addition, for the wind turbines in the near future.
- Lack of accurate representation of reactive power characteristics for wind turbine models has been found to be one of the biggest issues for future transmission planning purposes. More attention to the reactive power characteristics are requested while developing wind turbine models.

## 7. Conclusion

The amount of wind energy interconnected into the grid has been growing enormously in the last decade. As a result of this increase, the RTOs such as SPP and ERCOT have been making several changes to the standards, protocols and policies. All the changes aim to ensure the reliability of the grid, lower economics and treat wind power plants close to conventional power plants to the extent possible. Some of the most important changes in SPP include the transition to integrated market place, including wind as a dispatchable variable energy resource, improvements in modeling practices, and introduction of hub concept. ERCOT has been facing various technical challenges posing a threat to grid reliability due to high levels of wind penetration. The led to the most critical changes such as sub synchronous control interaction studies in the generation interconnection process, requirements for frequency response, stringent reactive power criteria and wind forecasting methodologies.

The impact of these changes on the wind industry was analyzed in great detail and the limitations in the currently available wind turbines and wind farms were discussed in the paper. The requirements and the capabilities, that the future wind turbines and wind farms need to possess, as a result of the changes were recommended and classified into three areas namely research directions for wind turbines, research directions for wind farm developers and future modeling requirements. The future

wind turbines should include SSCI mitigation strategies, provide frequency response, increase reactive power support and comply with the newly developed standards. Similarly, the future wind farms should include improved wind forecasting methodologies and faster SCADA. Finally, further research should be conducted to develop non-proprietary or generic models to represent all wind turbines and to improve the accuracy of existing wind turbine models with proper validation techniques.

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